

Beryllium erosion/transport from ITER main chamber wall and validation progress

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PFC Meeting May 2005, PPPL

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A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago



ITER Plasma Facing Component Tasks

- **Initiate analysis of ITER mixed material (Be/C/W) Plasma Facing Component performance. (ANL, LLNL)**
(J.N. Brooks, J.P. Allain, M. Nieto, T. Rognlien)
- **Supporting science: PISCES beryllium/carbon mixed-material experiments modeling. (ANL, UCSD)**
(J.N. Brooks, J.P. Allain, M. Nieto, R. Doerner, D. Nishijima)

PFC sputtering erosion/redeposition (E/R) issues for ITER

- *Lifetime of first wall beryllium coating due to sputtering erosion.*
- *Lifetime of carbon (tungsten) **divertor** with mixed material (Be/C) sputtering/transport.*
- *Tritium codeposition in deposited carbon and beryllium.*
- *Plasma contamination by divertor and wall sputtering.*

--E/R analysis helps define: 1) choice of surface materials, 2) choice of plasma regimes, 3) tritium removal schemes, recoating frequency, etc.

--Previous studies have focused on single material divertor analysis; much less on **wall** and wall/divertor **mixed-material** effects; much less on PFC response with **convective** plasma boundary transport.

--US is the world leader in erosion/redeposition (and disruption/transient-response) fusion analysis (models, codes, test-facilities)*.

* Fusion Engineering & Design Special Issue 60(2002)

Initiate analysis of mixed material PFC erosion/redeposition performance for ITER

- Key issues: first **wall lifetime**, effect of transported beryllium on carbon (tungsten) **divertor erosion** and **tritium codeposition, plasma contamination**. Steps (2 yr goal):
- Method (follows FIRE-type analysis*): **Package-OMEGA**
- 1) Compute sputtering of ITER beryllium wall with and without plasma convective flux to wall.
- 2) Compute transport of sputtered beryllium to wall, divertor, plasma.
- 3) Mixed material code analysis of Be/C mixing/sputtering on the ITER vertical divertor target.
- 4) Compute erosion/redeposition, and surface-temperature dependent tritium codeposition in resulting growth layers of beryllium and carbon with inputs of oxygen flux to divertor and Q/Be and Q/Be-O codeposition rates.
- *J.N. Brooks, J.P. Allain, D.A. Alman, D.N. Ruzic, Fus. Eng. Des. 72(2005)363.

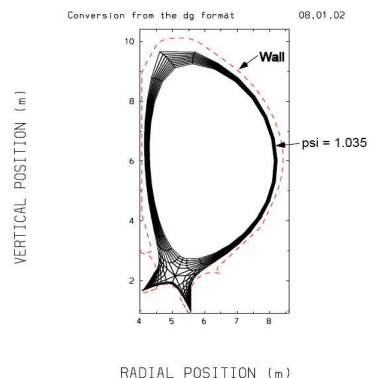
Package-OMEGA*

- **UEDGE/DEGAS:** D-T ion and neutral flux to wall, scrape-off layer (sol) plasma parameters
- **TRIM-SP, ITMC:** wall sputter yields
- **WBC+:** wall-sputtered beryllium transport in scrape off layer
- **REDEP/WBC:** divertor erosion/redeposition analysis
- **ITMC, SIBIDET:** mixed-material evolution, divertor sputter yields
- **BPHI-3D:** Sheath analysis
- **Data** (where available)

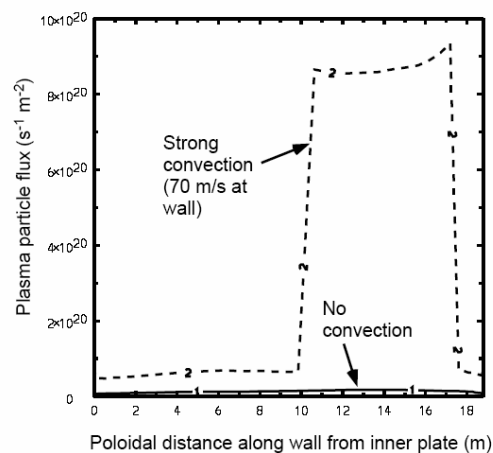
* Omnibus Modeling of Erosion Generalized Analysis

UEDGE ITER boundary plasma results (Rognlien)

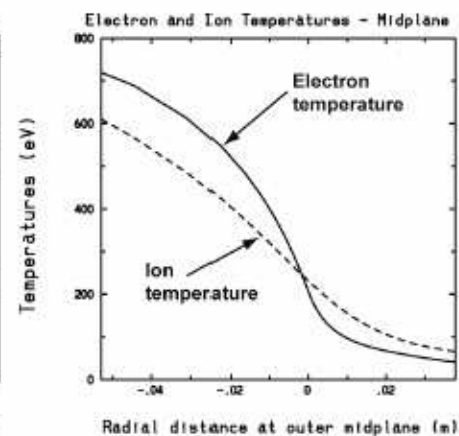
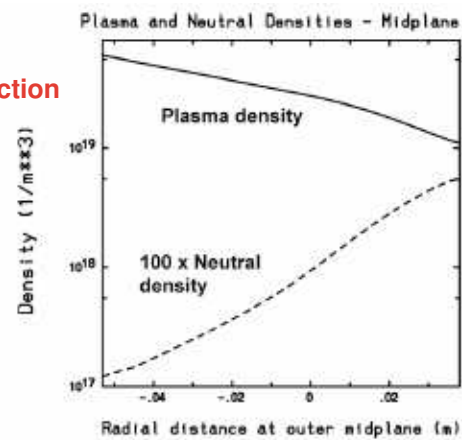
UEDGE plasma mesh (reduced number of flux surfaces)
corresponding to $\psi_{\text{max}} = 1.035$ to avoid second X-point



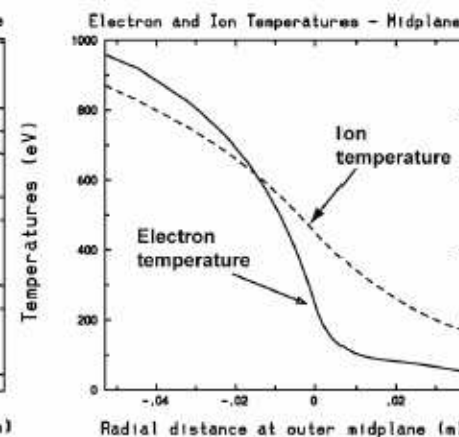
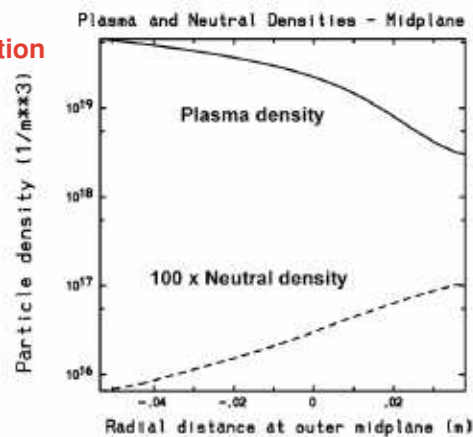
Ion flux to the "wall" (at $\psi = 1.035$) comparing
standard case and on with strong convection



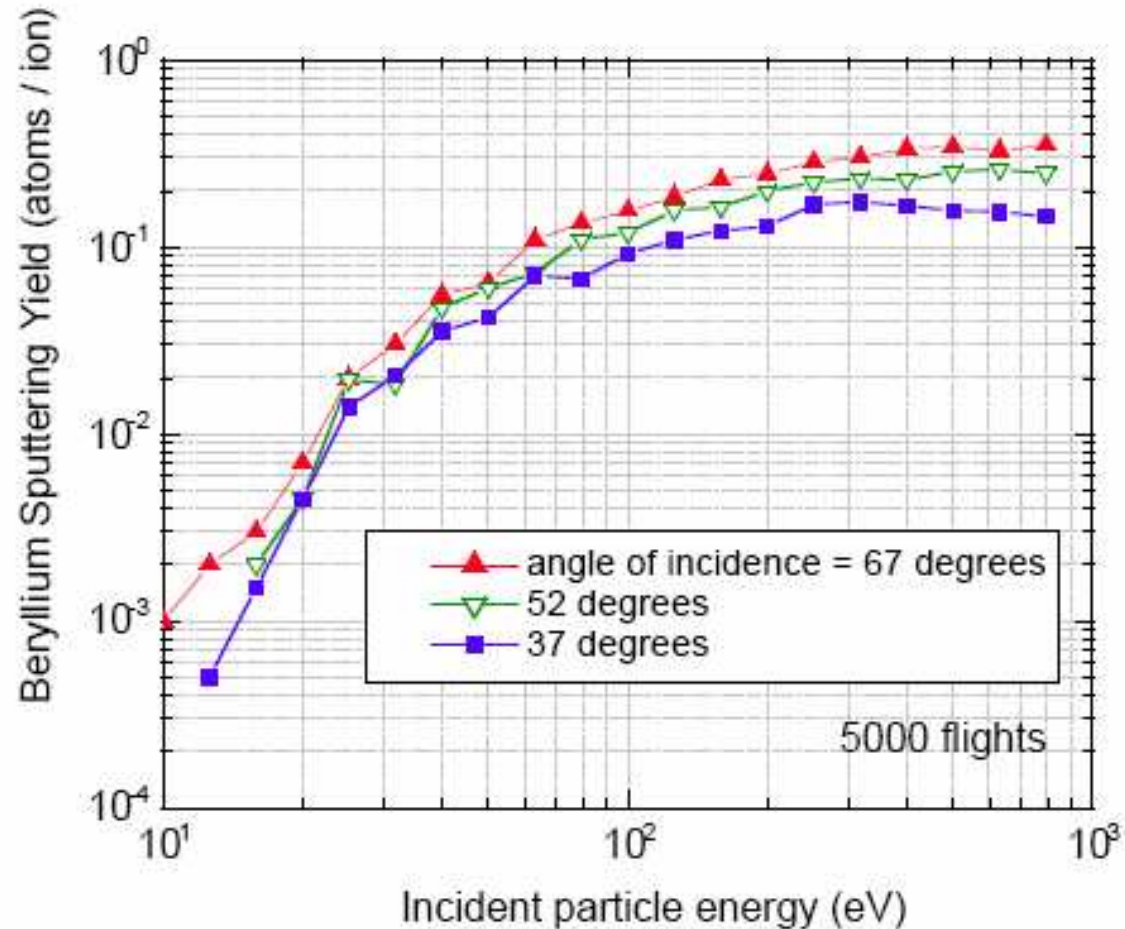
with convection



no convection



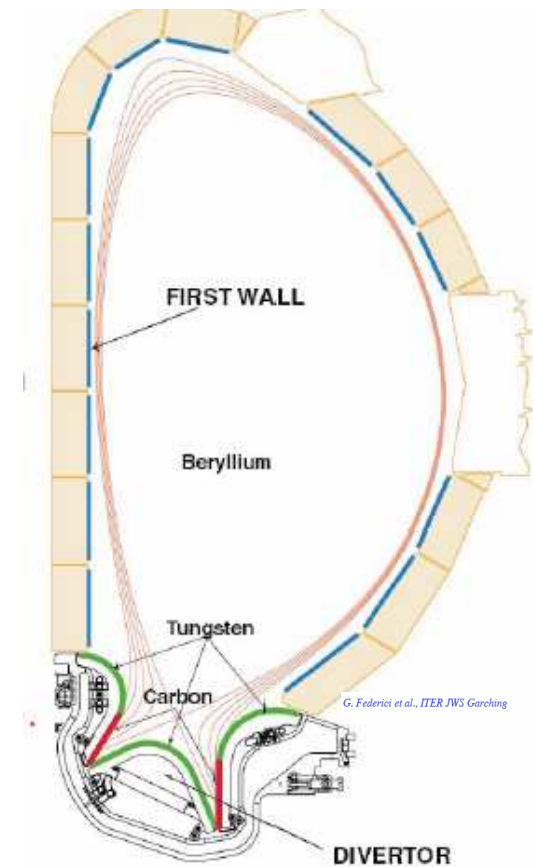
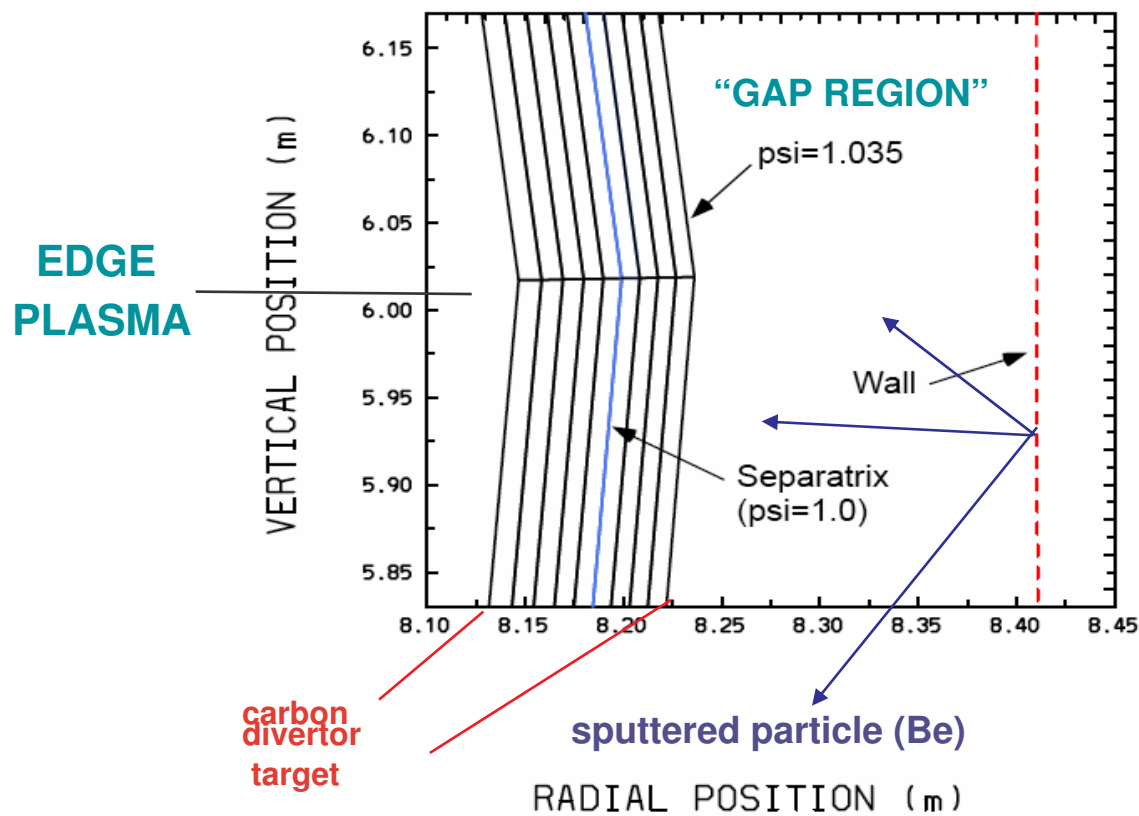
Sputtering yields for D^+ on Be with incident energies between 10 and 1000 eV, and with incident energies of 37°, 52°, and 67° (TRIM)



Detail of divertor-to-wall PACKAGE-OMEGA ITER calculation geometry

Flux surfaces at outer midplane for $\psi_{\text{max}}=1.035$

UEDGE Grid
Conversion from the dg format 08.01.02



Package-OMEGA wall sputtering/transport calculation/assumptions

- Wall beryllium sputtering computed using UEDGE ion and neutral flux (@45° D yields).
- Gas puffing not included.
- Plasma sheath at wall.
- Neutral beryllium transport: initial/simplified Be/plasma elastic collision model, electron impact ionization w/ADAS rates.
- Divertor-Wall “gap region” density, $n_e(x) = n_0 \exp(-x/\lambda)$
- Ionized, Be^{+k} , transport in gap region: initial/simplified collision model.
- Partially self-consistent code-coupling.

ITER Package-OMEGA preliminary results: beryllium sputtering and transport

Plasma Case	Sputtered beryllium current from wall	Peak wall erosion rate*
With convection	$3.9 \times 10^{22} \text{ s}^{-1}$	1 nm/s
Diffusion only	1.8×10^{21}	0.02

* w/o gas puffing

ITER Package-OMEGA: beryllium sputtering and transport, preliminary results

Plasma Case	Sputtered beryllium current from wall	Wall-sputtered fraction to carbon divertor target	Average beryllium growth rate on carbon divertor target*	Wall-sputtered fraction to edge plasma
With convection	$3.9 \times 10^{22} \text{ s}^{-1}$	5.1 %	1 nm/s	0.37 %
Diffusion only	1.8×10^{21}	50	0.6	3.7

* gross, not including sputtering/redeposition processes at divertor

ITER Package-OMEGA tritium/beryllium codeposition; initial, rough estimate

Plasma Case	Q/Be trapping data assumption	Codeposition for 400 s pulse
With convection	Mayer et al.* ("abundant" oxygen)	12 g T
	Causey et al.** (low/no oxygen)	2
Diffusion only	Mayer et al.* ("abundant" oxygen)	0.5
	Causey et al.** (low/no oxygen)	0.1

* (Q/Be ~ 0.3 @ 250 °C

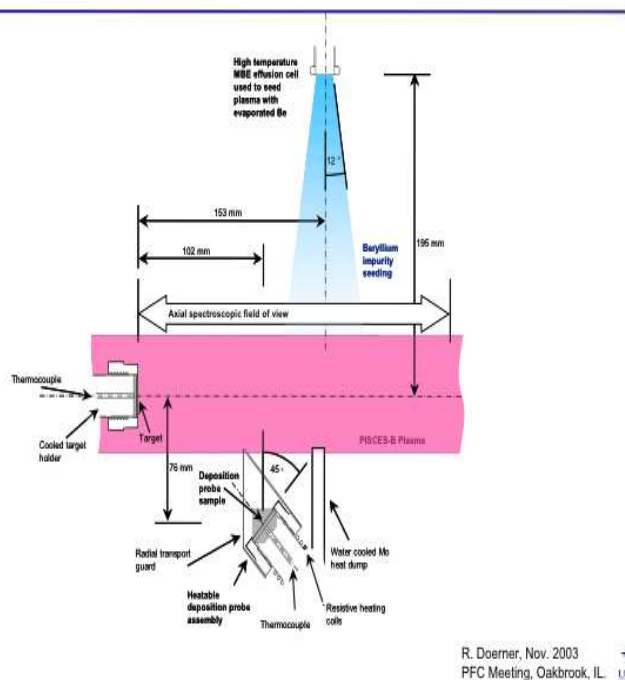
M. Mayer et al, "Codeposition of hydrogen with Be, C, and W", J. Nuc. Mat. 230(1996)67. M. Mayer et al., "Codeposition of deuterium with BeO at elevated temperatures", J. Nuc. Mat. 240(1998)84.

** (Q/Be ~ 0.05 @ 250 °C

R.A. Causey, D.S. Walsh, "Codeposition of deuterium with beryllium", J. Nuc. Mat. 254(1998)84. R.A. Causey, "Hydrogen isotope retention and recycling in fusion reactor plasma facing components", J. Nuc. Mat. 300(2002)91.

Modeling of PISCES mixed material; Be/C experiment

PISCES-B has been modified to allow exposure of samples to Be seeded plasma



- Purpose: Understand mixed-material Be/C sputtering and transport, Q/Be codeposition.
- Similar to expected conditions on ITER carbon divertor target subject to high beryllium flux from wall sputter/transport.
- Key code/data comparisons: Be-I photon emission and Be-I density profiles, surface growth of Be/C target.

Modeling of PISCES beryllium seeded mixed-material experiment

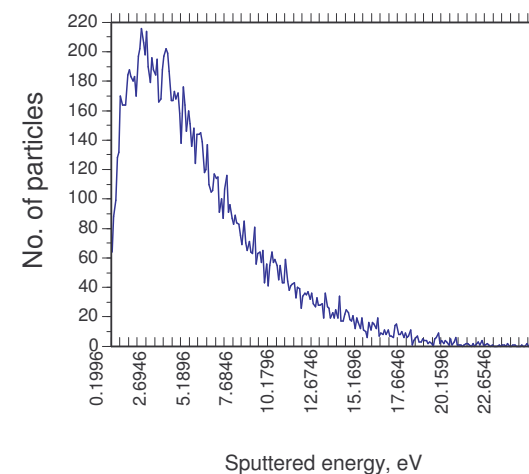
REDEP/WBC code simulation of 2.1 cm diameter carbon target bombarded by $T_e = 5, 7, 8$ eV, Be-seeded multispecies deuterium plasma. Key inputs from TRIM-SP code.

- $T_e = 5, 7, 8$ eV, uniform in plasma. $N_e = \sim 3.0 \times 10^{18} \text{ m}^{-3}$ at target center, uniform over target radially, radial variations (past-target) and axial variations in N_e per PISCES data
 - Pre-sheath field, radial diffusion coeff. per previous work (D.G. Whyte et al., Nuclear Fusion 41(2001)47.). Plasma Mach number varies from 1.0 at target to 0.2 at 20 cm axially from target.
 - Be/plasma-electron/ion collisions from full kinetic theory. Ion mass = 2.0 AMU in collision routine (corrections for D_2 , D_3 mass should make 2nd order difference).
 - Be/background-neutral collisions (elastic) using 5 mtorr D_2 @ rt.
 - Be atoms launched from points on the target per incident D^+ , D_2^+ , D_3^+ flux profile, with velocity per results of TRIM-SP runs w/ 40, 70 eV D^+ normal incidence on Beryllium-Carbide.
 - Detailed Be-I photon emission diagnostic simulated.
- ADAS rate coefficients (per T. Evans GA) for electron-impact ionization of Be-I, Be-II, at 5-8 eV, at $N_e = 2.5 \times 10^{18} \text{ m}^{-3}$. e.g., at 5 eV:
- BeI->BeII, $\langle \sigma v \rangle = 1.428 \times 10^{-14} \text{ m}^3/\text{s}$
 - BeII->BeIII, $\langle \sigma v \rangle = 5.171 \times 10^{-16} \text{ m}^3/\text{s}$

PISCES deuterium ion composition and sputter yields*

Plasma Species	Ion fraction	Sputter Yield			
		Be target	Be ₂ C target	Be target	Be ₂ C target
		40 eV	40 eV	70 eV	70 eV
D ⁺	55%	.0071	.0025	.0135	.0063
D ₂ ⁺	25%	.0040	.0019	.0100	.0053
D ₃ ⁺	20%	.0012	.0006	.0045	.0027
Y _{eff}		.0052	.0020	.0108	.0053

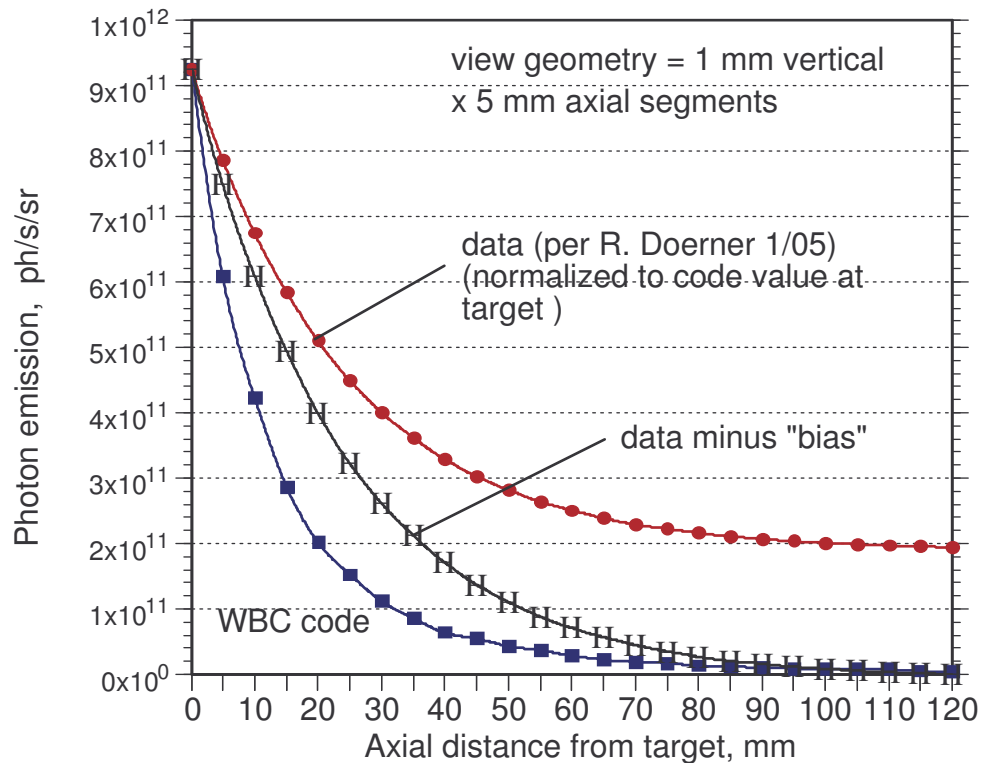
Sputtered Be distribution, Be₂C 70 eV



*Be/ion, normal incidence ions, TRIM-SP code

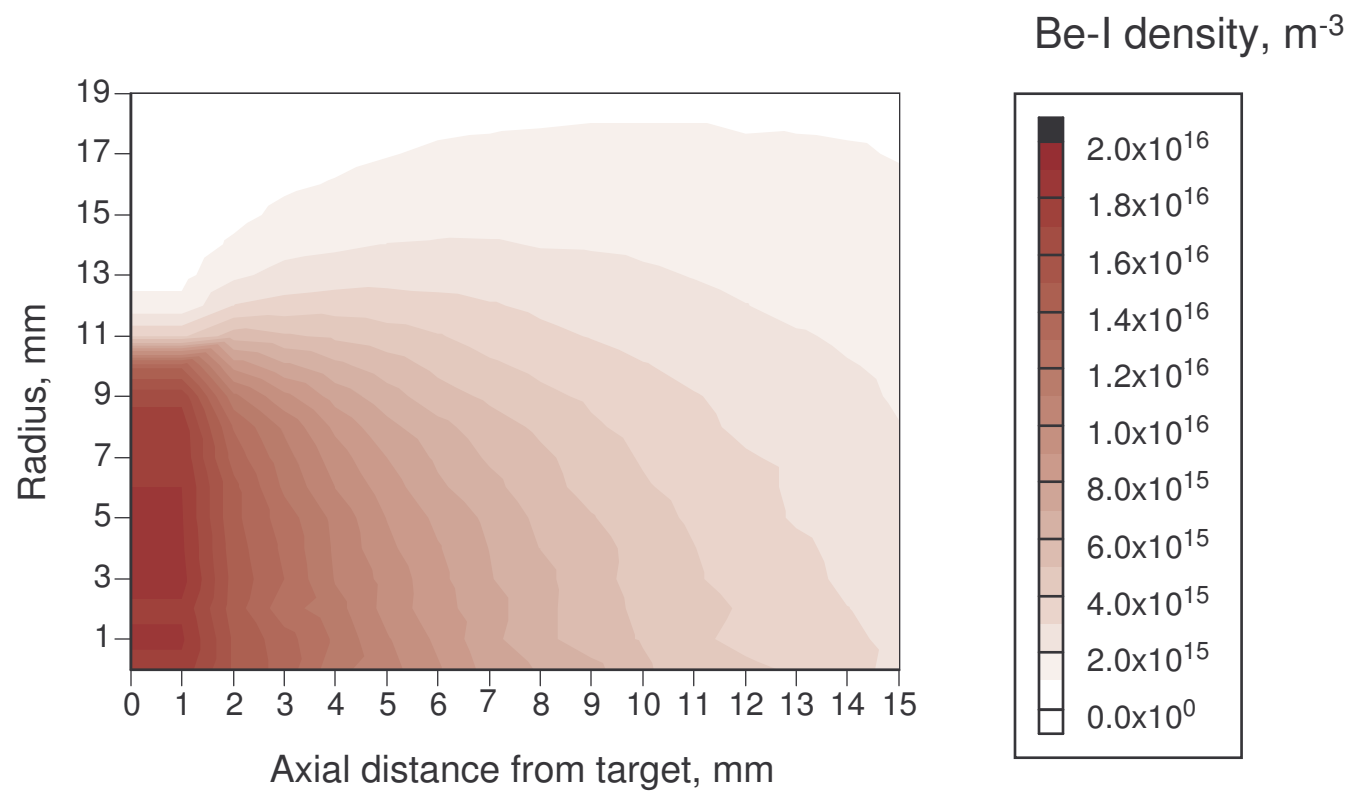
PISCES PHOTON DIAGNOSTIC SIMULATION

PISCES Be sputtering experiment- WBC computed
Be α photon emission axial dependence
(sample dia. = 2.2 cm, Te = 5 eV)



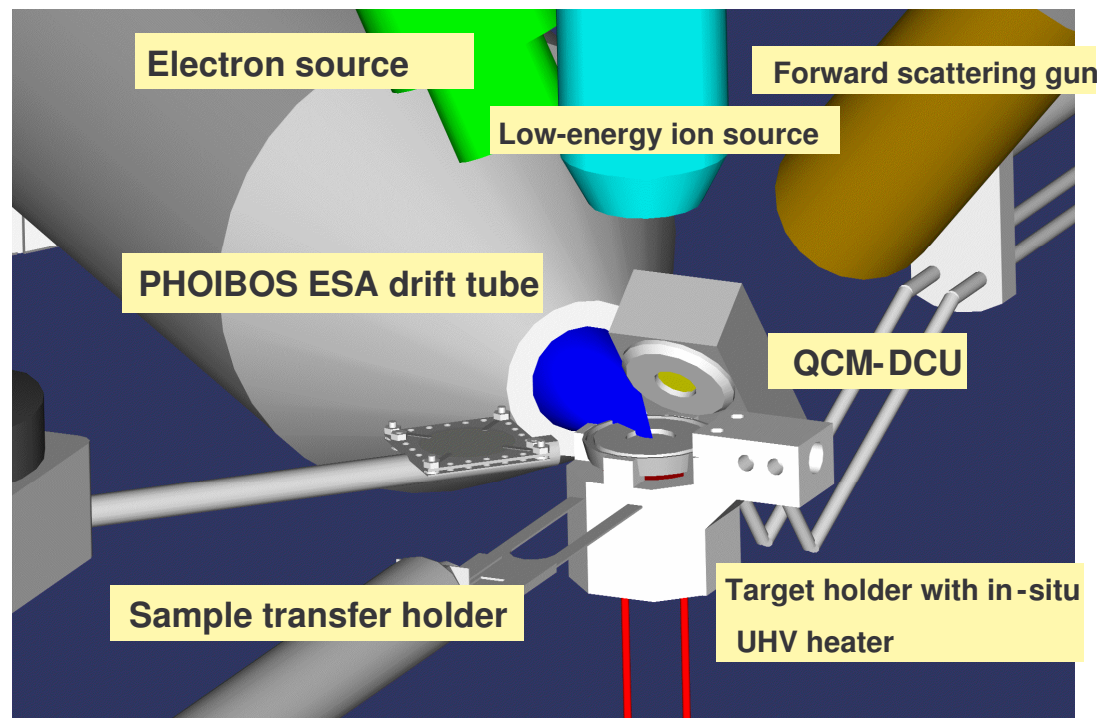
---code/data comparison is marginally acceptable

WBC code computed Be-I density, PISCES “8 eV Case; Nishijima et al. 3.14.05”



Be-C PISCES-B sample analysis in ANL IMPACT facility

- PISCES ATJ graphite samples exposed to Be-seeded D plasmas
- Samples delivered from D. Whyte (UW) after NRA measurements completed
- IMPACT facility conducting Auger analysis at both near-normal and glancing angles to examine regions of high Be concentration
- IMPACT will also conduct erosion and D recycling studies on some of these samples under intense, low-energy D bombardment



Next steps-near future

- Refine estimates of D-T ion and neutral flux to the ITER first wall and sputtered beryllium flux.
- Refine calculations for sputtered Be neutral and ion collisions with plasma ions/neutrals/electrons in divertor/wall region.
- Compute spatial profiles of beryllium transport to the ITER carbon divertor target, tungsten baffles, wall.
- **Continue code/validation effort on PISCES Be/C target.**
- **ANL IMPACT facility tests on exposed PISCES Be/C targets.**
- **DIII-D/DiMES Carbon “slot” experiment modeling.**

Conclusions

- **Preliminary results for ITER 1st wall sputtering/transport obtained with Package-OMEGA coupled code analysis show:**
 - Major effect of convective transport on wall erosion, codeposition.
 - Wall erosion rates may be tolerable (for low duty-factor ITER).
 - Substantial flow of wall material (Be) to divertor; might be beneficial?
 - Significant potential for tritium codeposition in redeposited beryllium.
- **PISCES Be/C ITER simulation mixed-material modeling and code/data comparison underway.**
 - **Be-I photon emission comparison being used to validate REDEP code mixed-material sputtering and transport models.**
 - **Be density, Be, C growth profiles under comparison.**